Two-Photon Absorption Induced Charge Generation for Single-Event Effects Studies

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Abstract—Nonlinear-optical (NLO) approaches were first introduced for the purpose of investigating single-event effects (SEE) in microelectronics in 2002. The primary approach utilized to date is based on two-photon absorption (TPA), in which two sub-bandgap photons are absorbed simultaneously by the material (typically silicon), creating a single electron hole pair. Recent efforts have focused on putting TPA SEE approaches on a quantitative footing. This paper discusses recent developments in that regard.

Keywords—TPA, nonlinear optics, NLO, SEE, dosimetry

I. Introduction

Two-photon absorption (TPA) was introduced in 2002 as a method of generating carriers in silicon for single-event effects studies [1], motivated primarily by the need to avoid the metal over-layers that have become increasingly problematic for optical approaches in recent-generation technologies, as is illustrated in Fig. 1. In TPA, carrier generation is highly concentrated in the high irradiance region near the focus of the beam, and the use of sub-bandgap optical photons permits carrier generation at any depth in the silicon substrate. This is particularly useful for SEE studies, permitting carrier injection from the "back side", through the silicon substrate, avoiding the metal stacks on the top side of the chip [1-4].

Over the past several years, significant effort has been expended towards putting the TPA SEE approach on a firm quantitative footing. From a historical perspective, the primary utility of pulsed laser SEE approaches has been qualitative in nature, and significant insights can be gleaned by considering only qualitative aspects. As the TPA SEE approach has matured, however, it has become necessary to develop the ability to: (i) monitor and correct fluctuations in the laser system operating point during an experiment; (ii) set the system to a pre-defined operating point prior to an experiment; and (iii) correlate experiments performed at different times, with different experimental configurations, or in different laboratories. This paper summarizes recent work in this regard.

II. Quantifying TPA SEE Measurements

The fundamental challenges to developing a quantitative understanding of the TPA SEE approach fall into two distinct categories: (i) having a complete understanding of the pulse delivered to the device under test, and how this understanding depends on experimental parameters, and (ii) understanding quantitatively how the charge deposition profile generated in the silicon (or other material) depends on the characteristics of the optical pulse determined from (i).

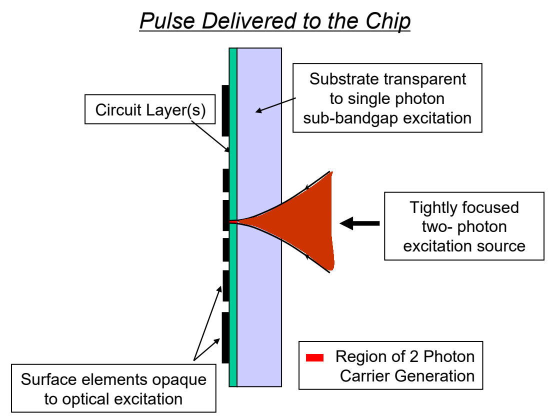

Fig. 1. Schematic representation through-wafer TPA excitation [1].

On the experimental side, a dosimetry approach for TPA SEE was introduced in 2014 [5] (optical dosimetry is more analogous to that used for dose rate sources, than for broad-beam ion sources). The complication for TPA, as compared to the relative simplicity of above-bandgap excitation, is that the quantity of deposited charge and the charge deposition profile are dependent on three independent parameters: (i) the laser pulse energy, (ii) the focused laser spot size, and (iii) the pulse duration. The focused spot size is the more challenging parameter to characterize experimentally. The approach of [5] utilizes three on-line monitors, which, when taken together, permit determination of the focused spot size in real time. In addition to tracking the operating point of the experiment, the presence of real-time online monitors permits adjustments to the system operating point, as needed. These include the initial setup and adjustments to correct for a drift in the operating point during an experiment, and also adjustments for performing systematic experiments as a function of the pulse focusing properties, in an efficient manner, without the overhead associated with (tedious and time consuming) knife-edge measurements. Experiments performed over the past several years at NRL have verified that the TPA experimental operating point can be set to match that of any prior experiment, reproducible to within experimental error. In addition, the procedures implemented in [5] should permit quantitative comparison of TPA SEE experiments from different laboratories.

Inside the silicon, the accurate calculation of the carrier density distributions induced by two-photon absorption long has been a challenge for the community. This is, in part, because the complexities associated with accurately modeling the NLO response in the tight-focusing, thick-sample geometry typically utilized for TPA SEE investigations, and also because of the large number of nonlinear-optical parameters required as input that must be accurately characterized experimentally. NRL has approached this problem by adapting an existing NLO simulation software package, NLOBPM (Nonlinear Optical Beam Propagation Method), developed by the Van Stryland group [6] to the carrier deposition problem relevant for single-event effects [7]. NRL also has undertaken an extensive effort to accurately characterize the various NLO parameters. NLOBPM is capable of providing a quantitatively accurate description of the three-dimensional carrier density distributions created by TPA under experimentally relevant conditions appropriate for SEE investigations. Experimental validation efforts on a large-area bulk silicon diode give good agreement between experiment and simulation results [8].

The combination of accurate TPA dosimetry, TPA experimental control, and a robust code for calculating the TPA-induced carrier density distribution, opens the door to studies that previously weren't possible. As an example, Fig. 2 shows a comparison of TPA- and heavy-ion-induced charge collection measurements a large-area bulk silicon photodiode [9]. The TPA SEE data of Fig. 2 are for three independent data sets measured for three different focusing conditions (with focused spot sizes ranging from 0.92 µm to 5.73 µm). Laser and heavy-ion data are plotted together and labeled "LET_{EFF}". The deposited charge values are calculated using NLOBPM and the experimentally determined sensitive volume [9], and converted into an effective laser *LET* (linear energy transfer) using:

$$LET_L = 96.5 \times Q_L / z, \qquad (1)$$

where LET_L is the laser-equivalent LET in MeV·cm^2 mg^{-1}, Q_L is the laser-deposited charge (in pC) within the sensitive volume, and z is the depth of the sensitive volume. All parameters used in determining LET_L are measured independently, and the data of Fig. 2 were plotted with no adjustable parameters. The level of agreement between the three TPA data sets plotted in Fig. 2, with zero adjustable parameters, requires (i) accurate experimental measurement of all relevant parameters, (ii) accurate values for the NLO parameters that are input into the NLOBPM calculation, and (iii) accurate representation of the material NLO response by the NLOBPM code.

The results presented in Fig. 2 are part of a larger effort to develop a correlation between TPA pulsed laser SEE measurements and measurements performed under heavy-ion irradiation, and illustrate the validity of an equivalent LET approach for correlating laser and heavy-ion measurements for the bulk silicon diode of this study.

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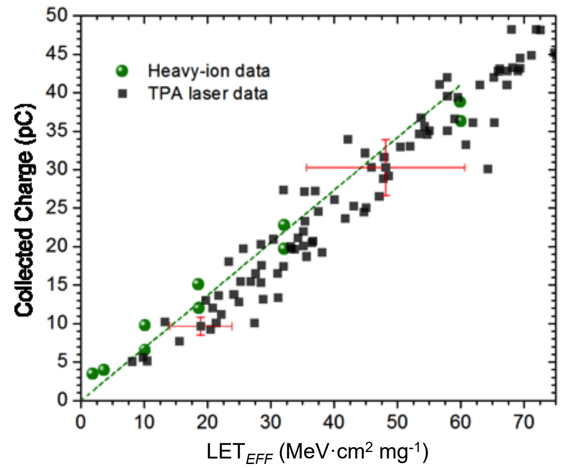

Fig. 2. Comparison of TPA- and heavy-ion-induced charge collection data, plotted on the same scale, as a function of an effective linear-energy transfer (LET) parameter for a bulk silicon diode. The TPA data include three different focusing conditions [9]. The error bars for TPA collected charge (±12%) are based on pulse-to-pulse fluctuations in the laser pulse energy, and errors in the deposited charge (±26%) are determined by the uncertainty in the experimental parameters that are used in the NLOBPM calculations [9].

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